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Spacecraft Beacon Monitoring for Efficient Use of The Deep Space Network

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ABSTRACT

This paper describes a new way of supporting highly autonomous missions being considered for use on upcoming NASA missions to Europa and Pluto. Each spacecraft will have on-board intelligence to determine whether or not it is healthy and when ground contact is needed. It will transmit one of four messages to the ground instead of normal full engineering telemetry of the spacecraft health. These messages will be monitored by a ground station, and, based on the urgency of the message, the Deep Space Network (DSN) will schedule an antenna to receive telemetry. Deep space missions traditionally schedule ground antennas to receive engineering telemetry up to several times per week. This new approach can reduce the monitoring time to a few minutes per day and engineering telemetry reception to once every several weeks. The end-to-end system design and operational strategy for this monitoring concept are described in this paper. In addition, alternative ground implementation approaches using different signaling and detection schemes and ground antennas are discussed. Since only a small set of messages is transmitted, it is possible to devise a signaling and detection scheme with a threshold a factor of 10 lower than the existing DSN schemes used for telemetry reception. The lower threshold allows weaker signals to be detected, which enables support of spacecraft at longer distances or use of smaller ground antennas. The economy of ground implementation options, however, depends on many factors, including the availability of existing 34-meter antennas, the number of user spacecraft, and the signal strengths
of these spacecraft. Finally, this paper describes a flight experiment planned for the first New Millennium Deep Space One (DS-1) mission.

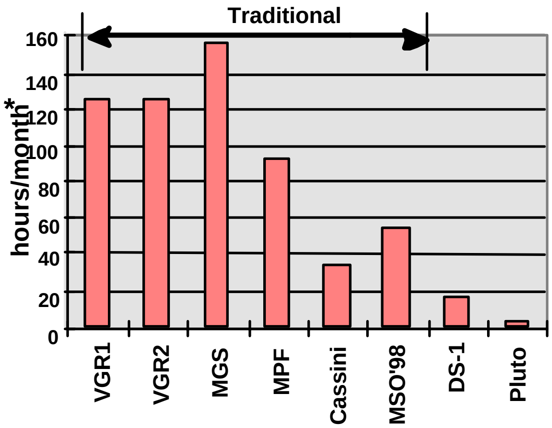
INTRODUCTION

The first New Millennium Deep Space One (DS-1) mission and Pluto Express are planning to demonstrate and use “Beacon Mode” for mission operations. The idea is to make use of the autonomy technology on board a spacecraft to allow the spacecraft to do self-monitoring and send reports to the ground using a very limited number of urgency-based messages. These messages will be monitored by a ground station, and, based on the urgency of the messages, the DSN will schedule an antenna to receive telemetry.

Traditionally, deep space missions have scheduled ground antennas to receive engineering telemetry up to several times per week. This new approach can reduce the monitoring time to a few minutes per day and engineering telemetry reception to once every several weeks, resulting in cost savings. Figure 1 gives the amount of antenna time for the traditional approach and the new approach, based on existing and planned deep space missions [1]

SYSTEM DESCRIPTION

A conceptual design is shown in Figure 2. The core elements include an on-board monitoring subsystem and a number of ground components,



* The antenna usage for DS-1 is based on an assumption of 1 track every 2 weeks, when using beacon monitor.

Figure 1. 34-m Antenna Time Needed to Downlink Engineering Data for Deep Space Missions in Cruise

which include a monitor station and a multimission coordination computer (MMC). The monitoring system requires the support of project operations teams and the DSN Network Planning and Preparation (NPP) Subsystem.

The on-board monitoring subsystem includes necessary flight software and part of the telecom subsystem. It is responsible for analyzing the engineering data to determine spacecraft health, reducing the health status to one of the four monitoring states (which are also known as beacon states or tone states), mapping the monitoring state into an appropriate monitoring signal, and transmitting the monitoring signal to the ground. In addition, the spacecraft is responsible for generating an engineering summary that will be transmitted to the ground and analyzed to determine the conditions of the spacecraft.

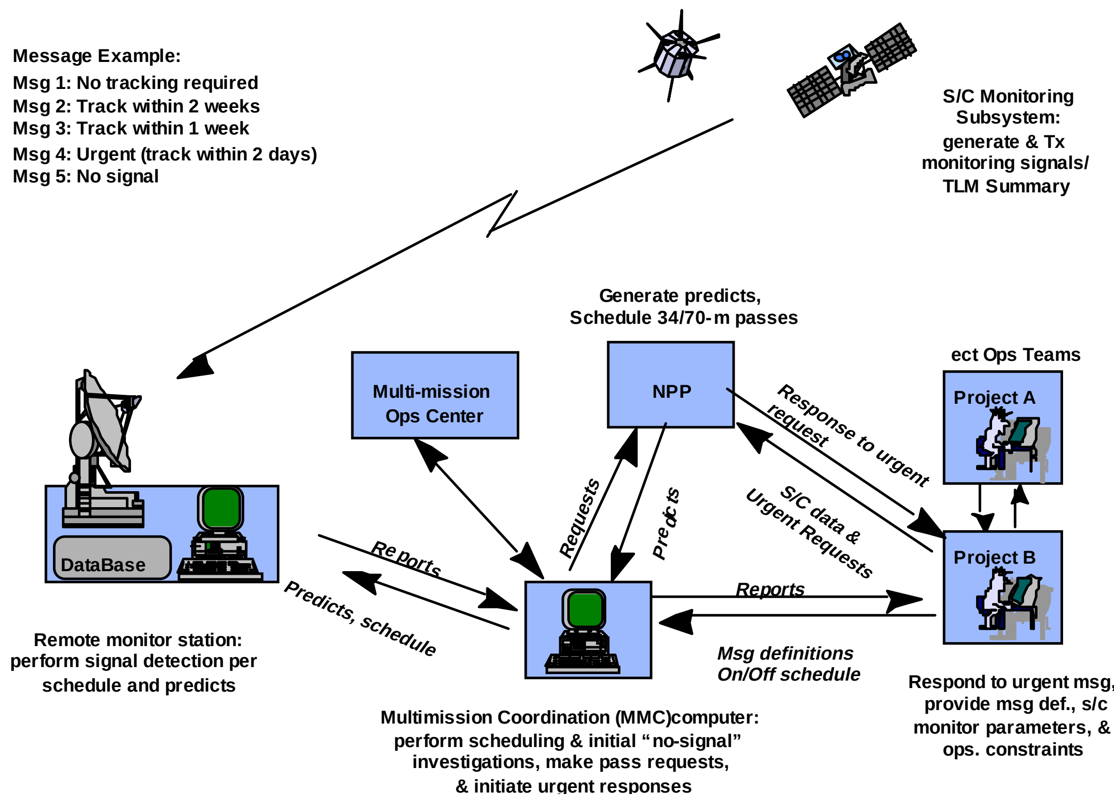
The monitoring station detects the monitoring signals using the schedule and predicts supplied by the MMC, and then sends the results to the MMC. The MMC is responsible for the operation of the system. It is where the detected messages are interpreted based on rules established by the project. It maintains a monitoring schedule for all spacecraft, and it makes pass requests for a 34-m or 70-m antenna and notifies the project, when needed. It also initiates urgent responses when triggered by an urgent message. The NPP provides frequency and antenna pointing predicts to the MMC, which then sends the predicts to the monitor station. In addition, the NPP is responsible for scheduling 34-m or 70-m antenna passes in response to the MMC's requests, as triggered by the detected messages. During a spacecraft emergency, the NPP will work directly with the project operations teams, bypassing the MMC.

The project operations teams are responsible for defining the monitoring messages and the required responses, and for supplying necessary spacecraft data to the NPP/MMC for scheduling and for predicts generation. They are also responsible for responding to urgent messages. Finally, the monitoring system is completed with the DSN 34-m or 70-m antennas, which track the spacecraft and send the data to the project operation teams in accordance with the NPP schedule.

SYSTEM OPERATIONS

The monitoring system normally is used for spacecraft health monitoring. It can also be used to allow a spacecraft to make requests for 34-m or 70-m DSN antenna tracks. It is intended for use during cruise and low-activity mission phases. When intensive interaction is needed between the spacecraft and the ground, the monitoring mode can be terminated by a ground command, or by an on-board computer. When a spacecraft emergency is detected by the on-board fault protection software, the spacecraft will revert to standard emergency mode operations and transmit low-rate telemetry to the ground.

When operating in the monitoring mode, each spacecraft will transmit its monitoring signal continuously and will at the same time maintain its ability to receive commands from the ground. However, there may be spacecraft constraints (such as the need to conserve power) that do not allow the spacecraft to transmit the monitoring signal continuously. In this case, a pre-agreed



TLM = telemetry S/C = spacecraft Tx = transmit msg = message

Figure 2. Monitoring System Conceptual Design

communication window can be established for monitoring purposes.

Each spacecraft will be monitored once per day, up to 1/2 hour per monitor. The four urgency-based messages may have the following definitions:

GREEN (message 1):	Spacecraft is nominal, no ground response needed.
ORANGE (message 2):	Need a DSN pass within two weeks.
YELLOW (message 3):	Need a DSN pass within one week.
RED (message 4):	Urgent, need a DSN antenna pass within 2 days.

The monitor state in general can be transitioned from a less urgent state directly to any one of the more urgent states. It will not be transitioned from a more urgent state to a less urgent one until the need for the more urgent state has been satisfied.

To allow sufficient time for the ground station to detect the transmitted message, the monitor message will not be changed more often than once per hour. However, when a RED state has been detected, the spacecraft will transmit the RED message immediately.

When the spacecraft is healthy, it will transmit a GREEN message either continuously or during a pre-arranged communication window. The monitor station will detect the message once a day and send results to the MMC. If a GREEN message is detected, the MMC will simply archive the result and forward it to the project operations team. This operation will be repeated daily until there is a change of the monitor state. The system as currently conceived does not require an uplink acknowledgment. As such, the spacecraft will not know if the message has been received by the ground. The spacecraft will therefore transmit the same message day after day if there is no change in the monitoring state.

When the spacecraft needs a 34-m or 70-m antenna pass, it will transmit a YELLOW, ORANGE, or RED message, depending on the urgency of the need. This message, after being detected by the ground monitor station, will trigger an appropriate response from the various ground elements as discussed in the next section.

The system (software) can be reconfigured to meet individual project needs and to accommodate specific operational constraints by modifying some of the operational parameters. These parameters include message definitions, their required response, message transition rules, length of the communication windows, frequency of monitoring, and performance requirements (e.g., probability of detection and false alarm rate, etc.). Many of these parameters are interrelated, and so changing one parameter may affect another. Care must be taken in selecting a set of workable parameters for system operation. The operational concept described above is based on a set of parameters judged to be reasonable and realistic for both the spacecraft and the DSN.

Operations Scenarios

Figure 3 graphically depicts the operations scenarios. An example is given below to illustrate the operations in detail. For this example, it is assumed that the spacecraft needs a ground track within one week and transmits a YELLOW message to the ground. After detecting the YELLOW message, the MMC will respond to this message according to the rules established by the project. The following is a list of actions after detecting a YELLOW message :

(1) The MMC sends a request to the DSN NPP/Scheduler for an 8-hour pass with a 34-m antenna in one week.

(2) The DSN Scheduler schedules a pass to take place five days later over DSS 15 (assuming availability) and informs the MMC and the project of the schedule.

(3) The spacecraft continues to transmit the same message (assuming no change of states during this period).

(4) The monitor station continues daily monitoring and reports results to the MMC (assuming no erroneous detection).

(5) The MMC takes no further action except archiving the message and forwarding it to the project.

(6) On the 5th day, DSS 15 or another 34-m station sends a command to the spacecraft one round-trip-light-time (RTLT) before the start of the scheduled downlink pass (or during a predetermined communication window) to initiate the downlink pass.

(7) After receiving the uplink command, the spacecraft stops other ongoing activities, if necessary, and starts to downlink as instructed.

(8) The DSN (DSS 15) receives and delivers the telemetry data to the project.

(9) The project analyzes the data and sends a command, via a 34-m station, to the spacecraft to reset its state to GREEN.

This completes the space–ground exchange for a YELLOW message. In the case of a “No Signal,” a spacecraft anomaly investigation will be conducted. The project operations team will be in charge of such investigation after being notified by the MMC.

END-TO-END SYSTEM DESIGN

The monitoring system is designed to support a large number of spacecraft. The major elements, as previously stated, include an on-board monitoring subsystem, ground monitor stations, the MMC, project operations teams, the NPP, and DSN antennas.

The on-board monitoring subsystem consists of part of the telecom subsystem and specialized software. The telecom portion of the monitoring subsystem generates and transmits monitoring signals representing the four monitoring messages. This function can be readily fulfilled by the on-board telecom subsystem using the Small Deep Space Transponder (SDST) currently being developed for deep space missions. No modifications to the SDST are needed in order to support the monitoring function. The main function of the flight software is to analyze engineering data, determine the health status of the

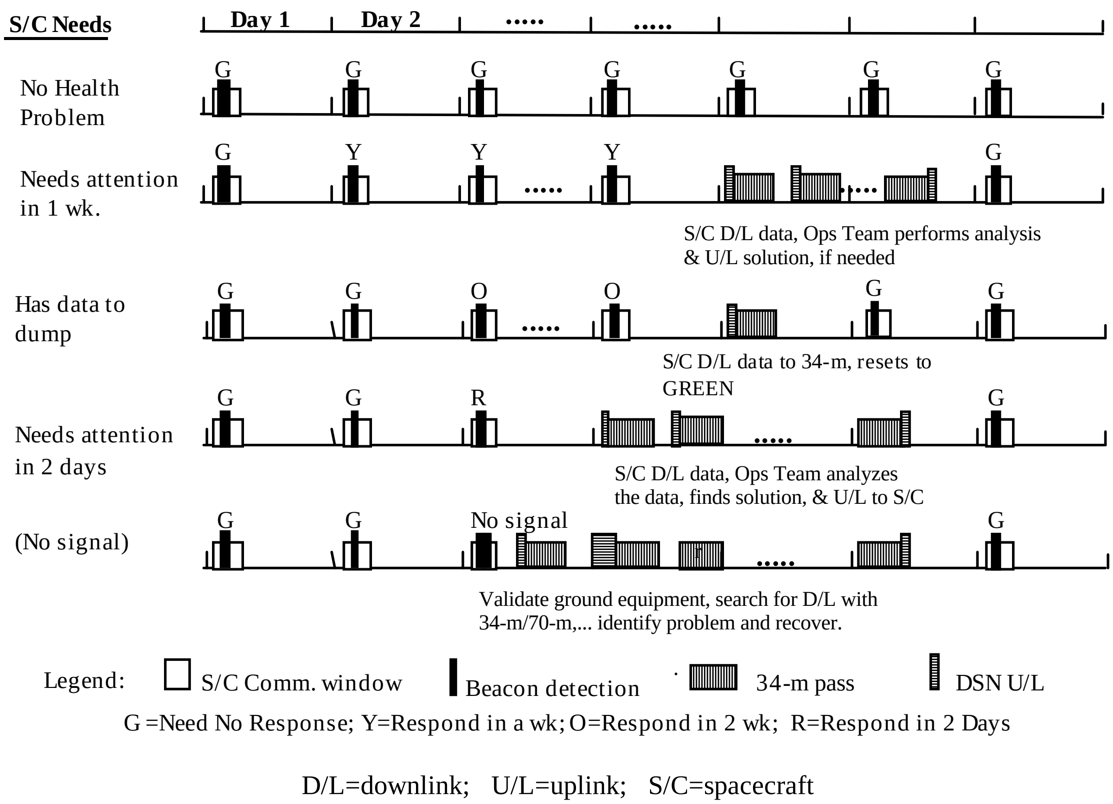


Figure 3. Operation Scenarios

spacecraft, and map the health states to one of the four monitor states (i.e., beacon states). In addition, the software generates engineering summaries.

Various options are available to implement the ground monitor stations and the detector. The ground monitor stations can either be new stations, each with a small antenna (8-m), or the existing DSN 34-m antennas, each equipped with a signal detector, or a combination of both. Assuming everything else being equal, a 34-m antenna can support a much greater communication range at the expense of a higher operating cost. The signal detector can be a coherent BPSK receiver traditionally used for deep space communications or a noncoherent tone detector. The latter can achieve a lower detection threshold but requires initial capital investments. The trade-off between noncoherent tones and coherent BPSK will be discussed later.

The MMC is simply a computer or a software package residing in an existing subsystem such as the NPP. The NPP and the DSN 34-m or 70-m antennas are existing equipment.

Flight Software System Design

The amount by which beacon monitoring reduces mission operations cost depends largely on the level of autonomy achieved on board the spacecraft.

Systems that can perform more robust recovery from anomaly conditions and provide flexible on-board data management enable innovative system designs for low-cost operations. In addition to on-board autonomy, there are two on-board technologies needed to enable the monitoring operation: on-board engineering data summarization and monitor message selection (which is also called beacon tone selection). The tone selection module is a software component that implements the functionality required to select tone states based on spacecraft health information.

The goal of on-board data summarization is to provide mission operators with concise summaries of spacecraft health at times when tracking is required. Engineering data channels are adaptively prioritized and stored between track periods. When a downlink pass is initiated, data transfer to the ground proceeds in priority order. The design is easily scaleable to accommodate changes in downlink bandwidth throughout the mission timeline.

A significant element of data summarization is a technique for creating derived channels or “transforms” of engineering data channels. The current set of transforms includes computation of high, low, average as well as first and second derivatives of selected channels. Another important element of on-board summarization involves replacing static alarm thresholds with adaptive alarm thresholds that are learned. Approximation functions create “behavior envelopes” that can be tighter than the traditional approach to anomaly detection. These function approximations are learned through training on nominal sensor data.

Summaries consist of several types of downlink “packets” stored by the on-board telemetry management system. Episode packets contain high-resolution engineering data (and associated transforms) for culprit and causally related sensor channels during the time just before and just after an alarm threshold has been exceeded. Snapshot packets contain low-rate engineering data for one time slice and accumulate continuously between track periods. Summary statistic packets contain top-level spacecraft mode/state information and information on the number of episodes. User summary packets are defined by the user a priori to capture important data around the time of pre-planned events. It is expected that missions will “fine tune” or calibrate summary content in early mission checkout activities by adjusting prioritization of data stored for downlink.

Monitor messages (or monitor states) are determined by on-board software based on fault protection health status and engineering data. Each message is relayed to the on-board executive (sequencing engine) via an inter-process communication system. The executive then commands the telecom subsystem to transmit an appropriate monitoring signal representing that message.

Ground System Hardware

The ground monitor station is a fully automated station; its operation is driven solely by schedule and predicts. The received signal is first down-converted, then sampled, digitized, and recorded. The digitized signal is processed by the signal detector. The detected signal is decoded by the message decoder, and the decoded message is then disseminated to the mission operations team and other users. A block diagram of the ground monitoring station is shown in Figure 4.

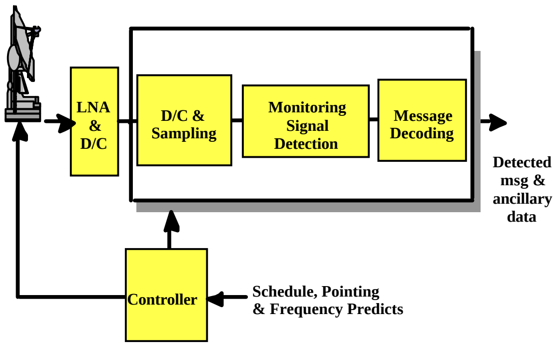


Figure 4. Monitor Station Block Diagram

Signaling and Detection Schemes

The monitoring system is designed to support future small, low-cost missions. It is highly desirable for the monitoring system to achieve a low detection threshold so that it can support distant spacecraft or relax the spacecraft antenna pointing requirement. The goal is to reliably detect the monitoring messages with 0 dB-Hz total-received-signal-to-noise-spectral-density ratio (Pt/No) using 1000 seconds of observation time. These missions are assumed to carry a low-cost auxiliary oscillator as a frequency source, instead of a more expensive, ultra-stable oscillator. The downlink frequency derived from an auxiliary oscillator is not precisely known due to frequency drifts caused by on-board temperature variations, aging, and uncorrected residual Doppler frequency. In addition, the downlink frequency also exhibits short-term drift and phase noise. All of these affect the selection of signaling and detection schemes and complicate the design of the signal detector.

Figure 5 gives an example of the frequency drift and short-term random fluctuation of the RF signal derived from an auxiliary oscillator. As indicated, the downlink signal exhibits both frequency drift and random fluctuation. Similar frequency drift and frequency jitters are expected for the SDST.

Assuming that the on-board temperature can be maintained to within 2^{o} C over a 24-hour period, the downlink frequency derived from an SDST-type oscillator is expected to have the following characteristics:

Initial frequency uncertainty:	2 kHz
Maximum drift rate:	0.05 Hz/s

Two signaling schemes that can readily be supported by the SDST can be applied to generate a signal set to represent the four monitor messages: traditional bit-based BPSK signals or tone-based signals. Coherent detection of BPSK signals and noncoherent detection of tones have both been considered for spacecraft monitoring applications. In the presence of unknown frequency and unknown phase, the noncoherent scheme offers a lower detection threshold for very-low-data-rate applications (e.g, to detect one of four possible messages with 1000 seconds of detection time). This is because the coherent scheme requires an accurate estimation of the unknown parameters (both frequency and phase). Obtaining an accurate estimate would require an integration time equal to the signal detection time (1000 seconds), or equivalently it would require that the phase-locked

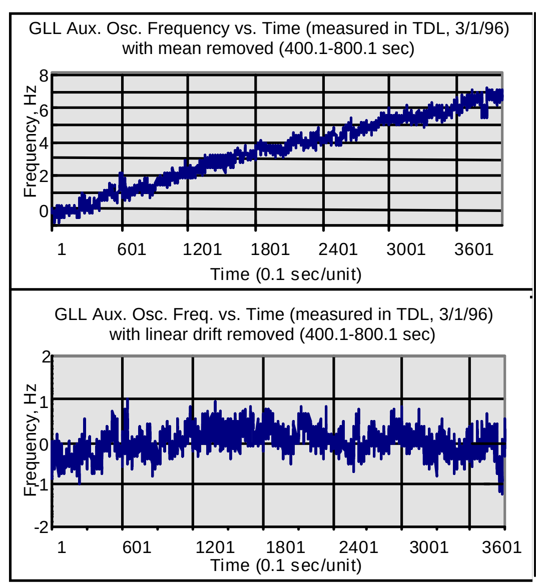


Figure 5. Galileo Auxiliary Oscillator Frequency vs. Time, as Measured in Telecommunication Development Laboratory (TDL), 3/1/96

loop bandwidth be narrowed to 0.001 Hz. This is not possible due to the frequency instability of the monitoring signal.

A tone-based signal structure is shown in Figure 6. Each message is represented by a pair of tones centered about the carrier. These tones are generated by phase-modulating the RF carrier by a squarewave subcarrier using a 90-degree modulation angle. The carrier **(** f_c) is completely suppressed. The resulting downlink spectrum consists of tones at odd multiples of the subcarrier frequency above and below the carrier. The higher harmonics are ignored; only the tones at the fundamental frequency are used to represent the transmitted message. Four pairs of tones are needed, one for each of the four possible messages. While the SDST can generate a wide range of subcarrier frequencies, instability of the downlink signal and detector complexity together constrain the selection of subcarrier frequency. For the DS-1 experiment, the four subcarrier frequencies (f_1, f_2, f_3 , and f_4 **)** are 20, 25, 30, and 35 kHz. Different sets of frequencies can be used for different missions.

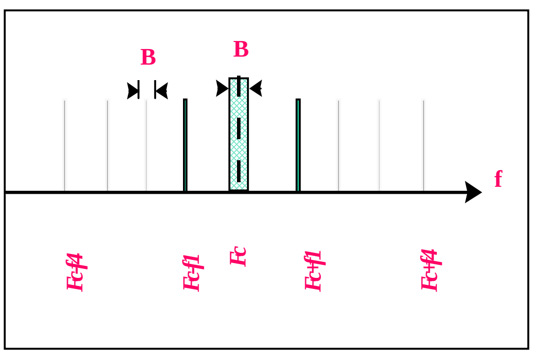


Figure 6. Signal Structure
B is the frequency uncertainty (2 kHz),
F_c is the carrier frequency, and
F_i is the i^{th} subcarrier frequency.

Performance Comparison: Coherent BPSK vs. Noncoherent Tones

Figure 7 shows the performance of coherent detection of BPSK signals and noncoherent detection of orthogonal tone pairs as a function of integration time (signal detection time), under the condition that the frequency drift is roughly linear or quadratic and the initial frequency uncertainty is within 2 kHz. Under this condition, noncoherent detection of orthogonal tone pairs would require about 0 dB-Hz of Pt/No. However, coherent detection of BPSK signals would require 15 dB-Hz of Pt/No with a carrier tracking loop bandwidth set at a practical limit of 2 Hz. A description of the noncoherent receiver structure and performance can be found in [2-4].

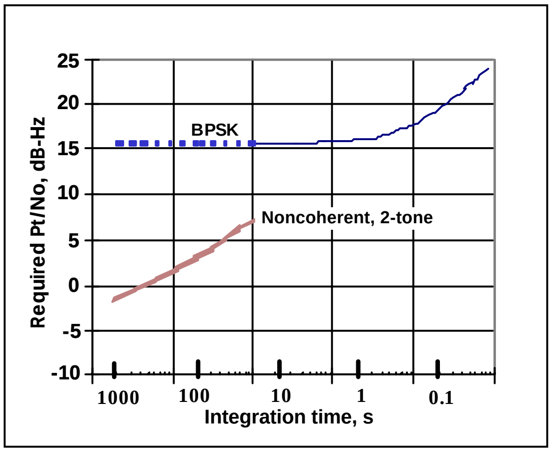
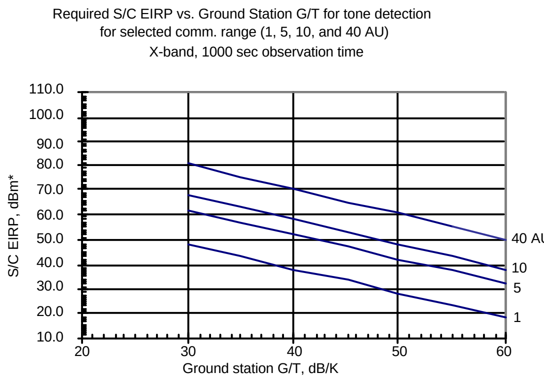


Figure 7. Required Pt/No vs. Integration Time

For a given spacecraft effective isotropic radiated power (EIRP), the 15-dB threshold advantage of the tone-based scheme allows the monitor system to support a greater communications range or to use a smaller antenna. The required spacecraft EIRP as a function of the monitor station G/T is given in Figure 8 for a detection time of 1000 seconds. However, even though the tone-based scheme has a performance advantage over the coherent BPSK scheme, other factors may affect the choice of a signaling and detection scheme.

MONITOR STATION IMPLEMENTATION APPROACHES

The performance advantage of the tone-based scheme, coupled with the low operating cost of small stations, appears to favor the use of a small antenna and the tone-based scheme. These advantages, however, are counter-balanced by the initial capital investments required to implement the new system. There are presently three candidate implementation approaches using different combinations of antennas and signal detectors:



*Including modulation and detection losses

Figure 8. Required Spacecraft EIRP vs. Ground Station G/T for 1000 Seconds Signal Detection Time

(A) Existing 34-m antennas using existing coherent BPSK receivers:

The four monitoring messages are represented by binary bits, which modulate the downlink carrier using BPSK. The monitor signal is received by a 34-m antenna and coherently detected by an existing receiver.

(B) Existing 34-m antennas with noncoherent tone detectors:

The four messages are represented by four pairs of tones. The monitor signal is received by an existing 34-m antenna and noncoherently detected by a tone detector.

(C) New stations with small antennas (8 m) and noncoherent tone detectors:

Similar to Option B, with a new monitor station replacing the 34-m antenna. This option requires a large capital investment.

Depending on factors such as the availability of a 34-m antenna, spacecraft EIRP, and the number of user spacecraft, one of the following will apply:

(A) If the existing 34-m antennas are available for monitoring, it is more cost-effective to use the

34-m antennas and employ either coherent BPSK or noncoherent tones. The tone-based scheme is needed if user spacecraft do not have sufficient EIRP; otherwise the traditional BPSK scheme is adequate.

(B) If the existing 34-m antennas are not available, a new station may be necessary. This station would have a small antenna and a tone detector. An antenna as small as 8 m would be sufficient.

FLIGHT EXPERIMENT

The objective of the Beacon Monitor Experiment (BMOX) planned for DS-1 is to validate key technologies and operational concepts for the new monitoring approach. The experiment consists of six elements, each of which has a specific objective:

(A) Engineering Summary Data Generation
The objective is to demonstrate that summary data provide all of the necessary information required for ground-based intervention (troubleshooting, maintenance, etc.) and assures the ground of overall spacecraft condition.

(B) Engineering Summary Data Visualization
The objective is to demonstrate ground software that assimilates summary downlink into concise and efficient displays.

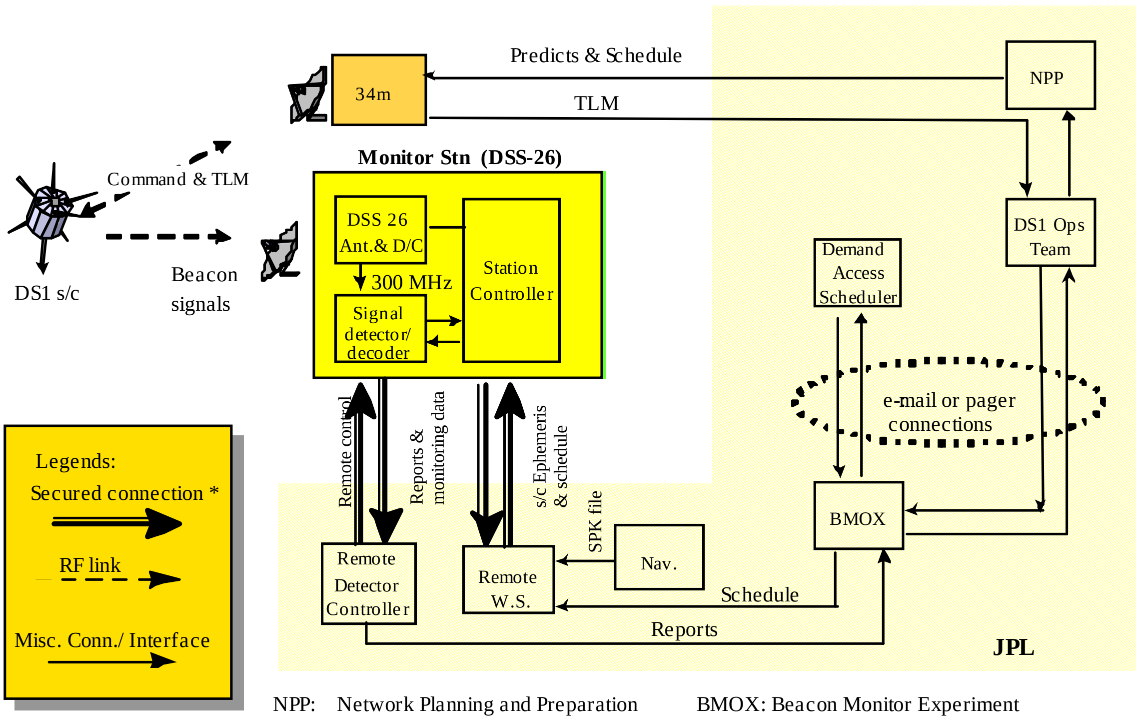
(C) Tone Selection
The objective is to demonstrate flight software functionality for setting and resetting beacon tones, to verify that a meaningful mapping from spacecraft health and status messages to urgency-based requests for ground action can be made.

(D) Tone Transmission and Detection
The objectives are (1) to verify that the transponder correctly generates and transmits beacon signals in response to flight software commands, (2) to verify that the beacon signal detector correctly detects the beacon messages in a realistic environment, and (3) to demonstrate schedule- and predicts-driven automated message detection.

(E) Multimission Ground Support
The objectives are to demonstrate a low-cost process to deliver beacon messages to the flight team and to demonstrate viable demand-based scheduling of DSN antennas for telemetry tracks.

(F) Operations Concept
The objectives are to demonstrate all technology components through use in DS-1 and to verify that beacon monitor operations can reduce flight project operations cost without increasing operations cost of the DSN.

The signal detection and message delivery system for BMOX is shown in Figure 9. DSS 26 will double as a monitoring station as well as a demand-access station. The beacon message is first received and decoded by the monitoring station at Goldstone and subsequently transmitted to the BMOX team at JPL via a secured link, such as the NASA Science Internet. BMOX in turn forwards the beacon message to the DS-1 mission operations team and other end users, including the Demand Access Scheduler, using e-mail or pagers. Depending on what message has been received, different activities will be carried out by the BMOX team, the Demand Access Scheduler, the mission operations team, and the DSN. If the received message is a GREEN message, no action will take place. If a RED message has been received, the Demand Access Scheduler will schedule a downlink track for the demand-access station to receive telemetry from the spacecraft. The Scheduler will notify the BMOX team of the schedule. BMOX will in turn notify the mission operations team and obtain its approval to carry out the downlink track triggered by the beacon message. One round-trip-light-time prior to the downlink track, a canned command will be transmitted to the spacecraft by the demand-access station or by another 34-m antenna station to initiate the downlink pass. The downlink telemetry will be received by the demand-access station, forwarded to the mission operations team and the BMOX team, and analyzed.



NPP: Network Planning and Preparation BMOX: Beacon Monitor Experiment
MMC: Multimission Coordination Computer W.S.= Work Station
* : via Telephone Network or NASA Science Internet

Figure 9. DS1 BMOX Signal Detection and Message Delivery System

The experiment will start shortly after the July 1998 launch of the DS-1 spacecraft and will last into October 1999. Key technology will be validated during the initial spacecraft checkout phase. Operational performance and cost benefits will be assessed at the end of the experiment. Operational use during the extended mission phase is being explored.

CONCLUSION

A conceptual system design and operational strategy have been established for the new spacecraft monitoring concept, along with candidate signaling and detection schemes and alternative ground implementation approaches. The operational strategy is based on a set of parameters judged to be realistic enough to enable the flight projects and the DSN to use this new monitoring concept for mission operations. In addition, an experimental signal detection and message delivery system design has been provided and is being implemented to support the DS-1 experiment. This experiment will be conducted using a DSN 34-m antenna as a monitor station and noncoherent tones as a signaling and detection scheme. The experiment will demonstrate end-to-end operations and will generate valuable data that will help in the assessment of the operational benefits provided by the new monitoring concept. While a particular signaling and detection scheme is planned for the experiment, it does not exclude alternative implementation approaches from being considered for the final operational system.

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